Weaning and Infant Mortality: Evaluating the Skeletal Evidence

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ABSTRACT Studies of prehistoric patterns of health and disease focus on interpretations of the evidence from hard tissue remains of past peoples. These interpretations are based on observations of living peoples and the sources of stress which may be expected to leave a record in their bones and teeth. One presumed source of stress that has received wide attention in the recent literature is weaning. The process of weaning is often associated with elevated risks of infant mortality and morbidity because infants no longer receive passive immunity from their mothers, and they are exposed to new sources of infection through the weaning diet. The process of weaning has also been tied to the duration of the contraceptive effects of nursing and the return of fecundity, which in turn provides information about birth spacing and population growth. Recently some of the basic assumptions about nursing and weaning, and their effects on morbidity, mortality and population growth, have been challenged, based on new technical and cross-cultural information. It is clear from the demographic literature that some studies based on skeletal samples tend to be too simplistic in terms of the causes of infant morbidity and mortality. This paper reviews current research which relates weaning and infant mortality to health and reproduction in past populations and evaluates studies of enamel hypoplasia and bone chemistry for reconstructing infant feeding practices in the past.

A central concern of biological anthropologists is to understand and explain cross-cultural and temporal variation in human populations. Variation in population size and rate of growth, family structure, infant care and feeding, and causes of morbidity and mortality are all areas of study in living populations, and skeletal biologists try to learn as much as possible about these same variables in samples from prehistoric and historic cemeteries. There has been considerable focus on the role of women in both modern and past populations, as seen in recent symposia on birth (Rosenberg and Trevathan, 1994) and breast-feeding[1] (Vitzthum and Bently, 1996), as well as various monographs, edited volumes (Hull and Simpson, 1985; Jelliffe and Jelliffe, 1978; Stuart-Macadam and Dettwyler, 1995; Popkin et al., 1986; Raphael, 1979; van Esterik, 1989; Winikoff et al., 1988) and reviews (Dettwyler and Fishman, 1992; Vitzthum, 1994). This interest has even spread to the popular science literature with featured articles on breast-feeding as cover stories in *Natural History* (Hrdy, 1995) and *Scientific American*

[1]We use this spelling of "breast-feeding" based on the one spelling given in each of the Oxford English Dictionary, the American Heritage Dictionary of American English and Dorland's Medical Dictionary. However we have seen the term appear as "breastfeeding" and as "breast feeding" in the current literature. Perhaps subsequent editions of dictionaries will reflect alternate current usage but we have chosen to use the traditional spelling.

(Newman, 1995). While research on birth and lactation in living human groups has grown considerably over the past few years, there has been concurrent growth of studies attempting to identify maternal behaviour and the relationship between infant feeding practices and infant morbidity and mortality in past populations. These studies have involved the identification and quantification of stress indicators such as enamel hypoplasia (Blakey et al., 1994; Lanphear, 1990; Moggi-Cecchi et al., 1994), Harris lines (Clarke, 1982; reviewed by Goodman et al., 1984; Larsen, 1987) and patterns of infant mortality (Cook, 1981; reviewed by Roth, 1992). More recently there have been attempts to estimate the age at which infants are weaned using bone chemical indicators (Fogel et al., 1989; Hühne-Osterloh and Grupe, 1989; Katzenberg, 1993; Katzenberg et al., 1993; Katzenberg and Pfeiffer, 1995; Schurr, 1996; Sillen and Smith, 1984; White and Schwarcz, 1994).

The increased attention paid to the subjects of weaning and infant mortality relate to the dual roles of nursing in providing immunity to the infant and suppressing ovulation in the mother. Therefore, fertility and infant health and survivorship have been tied to breast-feeding practices in living populations. There is also interest in the nutritional implications of the transition from breast milk to solid foods. Interest in the popular press relates to issues of infant mortality in the Third World, and to changing breast-feeding practices in North America (e.g., Van Esterik, 1989, 1995). A subject of interest in archaeology is the hypothesized change in infant feeding practices that may have accompanied a shift to domestication of plants and animals, and the resulting demographic changes (Buikstra et al., 1986).

There is a growing body of literature on the immunity provided to the infant by breast milk, and it is known that breast milk contains T and B lymphocytes, immunoglobins and antistaphylococcal factor, as well as other resistance factors (Hayward, 1983; Lawrence, 1994; Mestecky et al., 1991; Ogra and Ogra, 1979; Pickering and Kohl, 1986; Popkin et al., 1986; Wilkinson, 1981). The concentration of immunoglobins is highest in colostrum but their presence is maintained throughout lactation (reviewed by Lawrence, 1994). Goldblum and colleagues (1983, cited in Lawrence, 1994) measured IgA, lactoferrin and lysozyme through the second year of lactation and found levels similar to those measured at seven to 12 months. The immune system of the neonate is immature so this transfer of immunological components is extremely beneficial. There is evidence that factors in breast milk also induce the infant immune system to mature more quickly (Newman, 1995).

The relationship between nursing and the return of post-partum menstruation is highly variable (as reviewed by Ellison, 1995; Ellison et al., 1993; Knauer, 1985; McNeilly, 1993; Short, 1993; Vitzthum, 1994; Wood, 1994). This is, in part, dependent on whether the infant is exclusively breast-fed (Kennedy et al., 1989) and on suckling frequency and duration (McNeilly et al., 1983, 1994; Short, 1993). However, it is known that breast-feeding does lengthen the interbirth interval. Jelliffe and Jelliffe (1978) refer to some societies in which desired subsequent pregnancy is the reason for weaning a child. In 1988, an international group of researchers met in Italy to discuss breast-feeding as a method of regulating fertility and issued a "consensus statement on the use of breastfeeding as a family planning method" (Kennedy et al., 1989).

This review attempts to consider the ways in which the literature on the relationship between weaning and infant morbidity and mortality in living populations has been applied to the study of past populations. It does not aim to review that literature in a comprehensive way. Interested readers are referred to works by Dettwyler and Fishman (1992), Stuart-Macadam and Dettwyler (1995) and Vitzthum (1994). Weaning has been variously defined as the cessation of breast-feeding or the introduction of other foods while gradually reducing breast-feeding (reviewed by Dettwyler and Fishman, 1992). Lawrence (1994) mentions the Anglo-Saxon word "wenian," from which the term "wean" is derived. "Wenian" means "to become accustomed to something different." When weaning refers to the cessation of breast-feeding, it is an event. When it refers to the introduction of other foods and the gradual reduction

of breast-feeding (becoming accustomed to something different), it refers to a process. Some researchers (e.g., Popkin et al., 1986; Wood, 1994) use the term "complete weaning" to refer to the cessation of breast-feeding. It is difficult to be consistent with usage of the term in this paper because we discuss a number of different studies in which the various authors use the term differently. Whenever possible, we refer to weaning as a process, that is, the introduction of other foods and reduction of dependence on breast milk, and differentiate this from complete weaning which is the cessation of breast-feeding. Much of the literature on enamel hypoplasia tends to regard weaning as an event, that is, the cessation of breast-feeding. The bone chemistry literature varies since one of the chemical indicators of infant diet (strontium-calcium ratios) reflects the introduction of other foods, while the other (nitrogen stable isotope ratios) reflects the cessation of breast-feeding.

Dettwyler (1995a) has addressed the question: "at what age would human infants be weaned (cease breastfeeding completely) if the process were based only on physiological considerations?" Data from studies of nonhuman primates is presented along with references to information from a wide range of traditional societies to identify a "hominid blueprint" for weaning. Collectively, this information suggests that the cessation of breast-feeding among humans, in the absence of cultural influences, might be expected to be anywhere between 2.5 and 7.0 years of age. Dettwyler contrasts this to the much shorter duration of nursing typical of many individuals in modern North American society. This range of 4.5 years illustrates the variation that may be expected in past populations.

HISTORICAL DEMOGRAPHIC STUDIES OF INFANT MORTALITY, FEEDING PRACTICES, AND FERTILITY

We turn now to the historical demographic literature to illustrate some of the difficulties inherent in studying the relationship between infant feeding practices, infant mortality, and fertility in past populations. Demographers tend to approach the question of infant feeding practices from the point of view of how they operate in conjunction with a myriad of other socioenvironmental and demographic factors, such as fertility patterns, to explain why infant mortality rates change over time and vary according to place (see Swedlund, 1990). As such, breast-feeding practices per se have been accorded less prominence in the demographic literature than in the skeletal biology literature. Infant feeding practices are therefore considered to be important proximate factors in causality models for infant death on the one hand, but on the other they are recognized to be a rough point of entry to the identification and analysis of a constellation of other underlying features of social life and local ecology. Infant mortality is further tempered by large-scale processes, such as demographic and epidemiologic transitions, as well as by the biological cycles of pathogens like *Mycobacteria tuberculosis* whose epidemic waves operate over centuries (Bates, 1982). The growing literature on the emergence and resurgence of infectious diseases in human history has demonstrated how ecological change on both small and large scales can have dramatic epidemiological effects (Lovejoy, 1993; Morse, 1993).

Demographic studies at the local level have specified a variety of microecological factors that influence infant health. They are far too numerous to list here, but a few examples illustrate the complexity of the problem and the variety of components associated with infant death. Some researchers have studied the cultural context of differential survival among infants, such as the relationship between disparities in the distribution of resources (class and habitat) among various ethnic and religious communities (Sawchuk et al, 1985; Thornton and Olson, 1991); others have focused on household structure (Trapp et al., 1983); the relationship to women's work (Ball and Swedlund, in press; Dyhouse, 1978); or to a series of ecological, sociocultural and economic configurations (Ball and Swedlund, in press).

The complexity of the issue is well illustrated by Sawchuk's (1993) analysis of childhood mortality in Gibraltar in the 19th century and its relationship to fluctuations in water availability. He notes that while the

amount of rainfall affected the amount and quality of water generally available to all Gibraltarian households, other aspects of the local ecology (e.g., the case of water contamination) and political economy (e.g., water-support system and cost of potable water, coupled with marked economic inequality) filtered down to the household microniche (e.g., purchasing power, nutrition, extent of crowding, and sanitation) to produce marked differences in the quality of water ingested by children and, in turn, in the distribution of childhood mortality by socioeconomic group (Sawchuk, 1993). In other words, the relationship between child mortality and feeding cannot be fully understood without considering the quality of the food (including water) itself, as well as the child's micro- and macroenvironment. In fact, the quality of food available to infants and children represents an important path through which the environment acts upon their health (Mosley and Chen, 1984) and must be considered as important as breast-feeding or the provision of safe water supplies and sanitation (Motarjemi et al., 1993). The "weanling's dilemma" is recognized to be the health toss-up faced by an infant confronted with complementary foods contaminated with diarrheal pathogens when hygiene is poor against the probability that growth faltering will result when exclusive breast-feeding continues for too long (Hendricks and Badruddin, 1992; Hervada and Newman, 1992; Lutter, 1992; Martinez et al., 1994).

The long-standing importance of sanitary-social conditions in the child's environment is elegantly illustrated in Knodel and Kintner's (1977) historical demographic analysis of the relationship between breast-feeding and the age structure of infant death. They reanalysed historical data on breast-feeding and infant mortality for five late 19th- and early 20th-century populations in the United States and Germany. As one would expect, they found that where breast-feeding was rare or only practiced for a short period of time, infant mortality rates were not only higher than in populations where breast-feeding was more common, but cumulative infant mortality showed a sharp rise following the cessation of breast-feeding. In regions of Bavaria where extended breast-feeding was practiced, for example, fewer than 20% of liveborn infants died before the age of 1 year. In contrast, some 30–40% of liveborn infants died before their first birthday in regions in which there was little breast-feeding. This historical demographic work further demonstrates that the effects of breast- feeding on infant survival are critically modified by factors such as the extent of water and food contamination and levels of infectious disease in the infant's environment. As their data show, even when infants were breast-fed up to the age of 5 months and were, therefore, buffered from the deleterious effects of the environment by the nutritional and immunological benefits of breast milk, the infants were still confronted with contaminated introduced foods and high rates of infectious disease during the weaning process, resulting in a cumulative infant mortality rate of about 70/1,000 live births (see Figure 4 from Knodel and Kintner, 1977). While there is no doubt that breast-fed babies have lower levels of morbidity and mortality than do bottle-fed babies in the same environment, in proportion to the duration of breast-feeding (Clemens et al., 1986, 1990; Habicht et al., 1985; Popkin et al., 1990; Rosenberg, 1989; Victora et al., 1987), it is also evident that bottle-fed babies living in an environment characterized by high levels of sanitation and public health, effective medical initiatives targeted at improving infant survivorship, low levels of infectious disease, and safe, nutritious foods will have relatively lower levels of infant death than would be the case in a poor environment. This phenomenon helps to explain why infant mortality in the United States continued to fall unabated from 28.99/1,000 in 1950 to 10.96/1,000 in 1985 (London, 1993) in the face of declining rates of breast-feeding (up to the 1970s) (Dettwyler, 1995b; Knauer, 1985).

Mortality patterns detected at the local population level also need to be recognized as variants of a larger regional, and sometimes even global, demographic picture, as well as reflections of large scale cycles. The thrust of analyses from this perspective is to understand the total mortality profile of a population, how its component parts have changed over time, and the relationship that both the

profile and changes to it bear on other demographic parameters, such as levels of fertility. The epidemiological transition from epidemic to endemic disease patterns, for instance, was accompanied by changes in levels of infant death and by shifts in the causes that underlay them (see Kunitz, 1983; Leete, 1987; Omran, 1971; Young, 1988). As one would expect, the particular details of a demographic/epidemiologic transition depend on the social context in which it occurs and is clearly not a uniform process where high fertility and mortality rates are transformed to low levels of both (Swedlund, 1990). Even though nutrition and feeding practices may constitute a powerful explanation for infant mortality in a given population, there is no reason to expect the same explanation to apply in all other situations (Swedlund, 1990).

Although historical demographic studies in Europe and North America support the role of artificial feeding in high infant mortality (Kintner, 1985; Knodel and Kintner, 1977; Knodel, 1988; Wrigley, 1977), it has been far more difficult to add in a third variable, fertility, and study its relationship to breast-feeding and infant mortality in historical context (Kintner and van de Walle, 1967). This is because quantitative information on breast-feeding practices is generally inadequate for a quantitative analysis: The breast-feeding practices of specific women can rarely be linked directly to their fertility histories or to the survivorship or mortality of each of their children, even when family reconstitution methodology is used (McLaren, 1979; Thornton and Olsen, 1991). Consequently, the association between breast-feeding, infant mortality, and fertility in historical populations tends to take the statistically weak form of an ecological relationship, based on qualitative evidence.

A plethora of reconstituted family studies using parish and other registers, however, had demonstrated that infant deaths reduce interbirth intervals and, hence, affect fertility (e.g. Gautier and Henry, 1958). Indeed, it was historical demographic research that focused attention on postpartum amenorrhea and on lactation effects as explanations for differences in fertility within and between populations (Fildes, 1986, 1988, 1995; Henry, 1961; McLaren, 1979). Subsequent studies have confirmed a strong association between the duration of breast-feeding and the length of birth intervals, as well as support for the contraceptive effects of lactation (Dettwyler, 1987, 1988, 1995a; Goldman et al., 1987; Knauer, 1985; Konner, 1985; McNeilly et al., 1983; Short, 1993; Stuart-Macadam and Dettwyler, 1995). But there is still a body of vocal dissent on the issue (Hodgson, 1985; Santow, 1987) and perplexing heterogeneity in the duration of postpartum amenorrhea among women who appear to be following similar breast-feeding regimes (Vitzthum, 1994). It is also obvious that many factors work in concert to influence the fertility of populations (Ellison et al., 1993; Hern, 1992; Howell, 1979; Nag, 1962) and it is difficult to delineate with any precision the role played by breast-feeding.

INTERPRETATIONS OF WEANING IN SKELETAL SAMPLES

There are severe limitations on the amount of information that can be gleaned from archaeological skeletal samples. We cannot know the water quality, detailed causes of sickness or many of the other environmental conditions so critical for understanding infant morbidity and mortality. Nor can we hope to determine the effects of nursing and suppressed ovulation on individual women. We can, however, try to gain information on general trends in morbidity, mortality, fecundity and fertility through the methods of paleopathology, paleodemography and paleonutrition. There has been considerable progress in reconstructing environment, diet and health over time and space at prehistoric sites. Cohen and Armelagos (1984) provide a comprehensive look at progress on evaluating changes in health with domestication of plants worldwide and subsequent research has built upon some of the work presented in that edited volume. At the same time, it has become clear that interpretations must be made cautiously given the information that we do not know or that we may easily misinterpret given the limitations of skeletal samples (Wood et al., 1992). Specifically as Wood and colleagues point out, it may not be possible to determine

variation in frailty (the varying susceptibility of individuals to disease) or to solve the problem of selective mortality (our samples consist of those who died in each age group) (Wood et al., 1992). Research on stress indicators such as enamel hypoplasia and the differences in age at death for individuals that exhibit one or more hypoplasias (Cook and Buikstra, 1979; Goodman and Armelagos, 1988) attempts to get at the question of frailty in prehistoric samples. Goodman and colleagues have studied enamel hypoplasia in living peoples in an attempt to refine our understanding of the causes of hypoplasia and the most accurate ways of interpreting data from prehistoric samples (Goodman et al., 1987). Research on breastfeeding patterns through analysis of nitrogen stable isotopes in archaeological samples may add to our understanding of changes in fertility in a general sense by indicating whether the duration of breastfeeding changed over time (Fogel et al., 1989; Katzenberg, 1993; Katzenberg et al., 1993; Schurr, 1996). Another fruitful area of investigation is the study of historic cemetery samples where there is some documentation of health, disease, infant feeding practices, environmental and cultural variables that can aid in interpretation of skeletal data (see edited volumes by Grauer, 1995, and Saunders and Herring, 1995, and papers therein). The following discussion focuses on two types of evidence from archaeological samples that have been used to address questions relating to diet and stress in infancy and early childhood. The first is linear enamel hypoplasia and the second includes two different chemical indicators, strontium-calcium ratios and stable isotopes of nitrogen.

Evidence of stress in infancy and early childhood in the skeletal record

Cook (1979) was among the first researchers to note that skeletal and dental indicators of stress might relate to weaning. Her work focused on Woodland and Mississippian skeletal samples from the American Midwest. The causative effect of stress was thought to be a nutritionally inadequate weaning diet of maize gruel in the Mississippian samples. In their review of paleopathology, Buikstra and Cook (1980) referred to stress indicators, including enamel hypoplasia, but suggested that attributing their cause to such cultural factors as weaning was not well-founded at the time. However, their review has been cited (e.g., by Lanphear, 1990) for suggesting that enamel hypoplasia can be caused by disease and nutritional stress that occurs during weaning. In fact, many of the citations claiming support for a relationship between enamel hypoplasia and weaning in archaeological samples can be traced back to Cook and Buikstra (1979) (for example Lanphear, 1990, cites Buikstra and Cook, 1980, but Buikstra and Cook, 1980, cite Cook and Buikstra, 1979). Ironically, this is not what Cook and Buikstra claimed in their article. They were examining the prevalence of linear enamel hypoplasia, hypocalcification and hypoplasia-related caries (circular caries) in the deciduous teeth of infants and children from Middle and Late Woodland skeletal series from the Lower Illinois Valley. Deciduous teeth reflect prenatal stress (in fact the subtitle of the paper is "prenatal dental defects") and the caries that form in the hypoplastic bands and pits reflect diet and stress in the postnatal period. They compared the estimated age-at-death distributions of unaffected individuals vs. individuals affected by hypoplasia in the two temporal samples to determine whether there was differential selection for mortality in the two groups for both the Middle and Late Woodland periods. They found significant differences in the age-at-death distributions in the samples from both time periods. They then compared the points at which the age-at-death distributions of normal and affected individuals diverged to identify stressful time periods in the lives of these children. For the Middle Woodland sample they identified maximum divergence in the age period 24–30 months whereas in the Late Woodland sample they identified maximum divergence in the age group 3 years and above. From this observation, they attribute the contrast between the Middle and Late Woodland samples to differential mortality in the preweaning and postweaning periods, with the Late Woodland sample showing more severe selection after weaning. It was assumed that weaning (the

cessation of breast-feeding, in this case) occurs around 3 years of age for both time periods. The authors use a general estimate of weaning age of 3 years because their interest is in the potential of death due to malnutrition from weaning diets, and therefore a precise knowledge of weaning age is not necessary.

The association of hypoplasias with weaning has rested on the identification of the age of the individuals at the time of the development of the hypoplasias (Goodman et al., 1984). Sarnat and Schour's (1941) early study of 60 individuals with enamel hypoplasia from the Chicago area found that most hypoplasias (67%) occurred during the first year, while another 31% occurred during the next 2 years. Goodman et al. (1984) challenged the long-held assumption based on Sarnat and Schour's work that the age-associated timing of hypoplasias is due to biologically determined developmental changes that are fixed or constant in all human populations (meaning that we would expect all human samples to show the highest frequencies of hypoplasias in the first year after birth). Examination of permanent teeth in 111 adult and adolescent skeletons from Dickson Mounds, Illinois, revealed that hypoplasias are most common between 2 and 4 years with a peak frequency of 2.5–3.0 years in the Middle Mississippian group vs. 3.0–3.5 years in the pre-Mississippian group. They attribute this concentration of hypoplasias to a poor weanling diet of maize, citing a master's thesis by Cook (1971) which argues that weaning to maize would have created nutritional stress and probably increased the chances for the occurrence of hypoplasias, particularly for the Mississippian period populations. However, they do not discuss their reasons for assuming that weaning took place between 2 and 4 years in the Dickson Mounds populations or other issues surrounding the complexities of the weaning process. They also do not discuss whether they eliminated individuals with tooth wear from their sample of observations since wear would remove the evidence for hypoplasia in the youngest age categories.

In a study of just over 100 enslaved individuals of African origin from Newton Plantation, Barbados, dating from AD 1660–1820, Corruccini and colleagues (1985) and Handler and Corruccini (1986) argue that the modal age of linear enamel hypoplasia (LEH) formation, 3.25 years, correlates with the historical evidence for a relatively late weaning age among Barbados slaves at 2 to 3 years. They note that in the year following weaning, mortality and morbidity risk were at their postnatal peak, including the frequency of hypoplasia formation. More recently, Jacobi and colleagues (1992) identified three cases of congenital syphilis in the Newton Plantation sample which contribute to dramatically increasing the frequencies of enamel hypoplasias in the total sample, because these individuals show several times the number of hypoplasias than are present in the remainder of the series. This would appear to diminish the argument for using enamel hypoplasias as indicators of weaning in this sample. However, the authors argue that weaning stress is still demonstrable from the timing of the disturbance of enamel development even though it is not clear why we should expect a high frequency of morbidity from 6–18 months after the presumed causal event, which is weaning.

Goodman and colleagues (1987) reported on their examination of 300 living children from five villages in the Solis Valley of highland Mexico. They found that most defects appear to develop between 12 and 36 months. This peak period is earlier than that which has been found in archaeological populations where most researchers report a range between 24 and 48 months. The peak ages of occurrence in the Mexican sample are also similar to another study of contemporary Jordanians reported by Alcorn and Goodman (1985). Both of these studies on living individuals note the coincidence of the similarity between the peak ages of occurrence of enamel hypoplasias in these two populations and the reported mean age at weaning, which is said to between 1 and 2 years. In this case, it should be noted that peak frequencies of LEH and weaning age are identified as coinciding instead of one preceding the other.

Lanphear (1990) reported that the peak age of occurrence of enamel hypoplasias in the 19th-century Monroe County Poorhouse

Cemetery sample is between 2.5 and 4.0 years. She concluded that stress associated with weaning would likely have occurred earlier in this group as compared to prehistoric hunter/gatherers and agriculturists but not as early as modern industrial groups. This conclusion is based on the premise that stress, as evidenced by hypoplasia, is an indicator of weaning.

More recently, Moggi-Cecchi and coworkers (1994) examined a sample of 83 skulls from individuals who lived in Florence during the 19th century. These individuals are personally identified and the majority were of low socioeconomic status. The researchers found that wide "grooves" with prolonged duration are concentrated between 2.0 and 2.5 years whereas "lines" occur primarily between 2.5 and 3.0 years. Historical sources indicate a weaning period between 12 and 18 months. The authors suggest that these results reflect the following risk factors: a gradual loss of nutrients supplied by human milk, an increased contact with pathogens from the external environment, and a reduction of the immunity provided by human milk. They use these factors to argue for a relationship between the normal weaning period and hypoplasias that formed after that period.

In a critical review of the hypothesis linking enamel defects and weaning, Blakey and colleagues (1994) documented the prevalence of enamel hypoplasias in the dentitions of 27 enslaved African Americans from 18th- and 19th-century plantation sites in Maryland and Virginia as well as 75 individuals from the First African Baptist Church cemetery in Philadelphia who would have been free wage laborers at the time of their deaths. Their observations of calculated peak ages of occurrence of enamel defects showed that most formed between 1.5 and 4.5 years of age, and they note that similar results were reported for a South Carolina plantation sample (Rathbun, 1987). On the other hand, Blakey and coworkers (1994) report historical information that indicates that enslaved African-American women were required to complete weaning between 9 and 12 months of age of the infant "in order to exploit their maximum productive and reproductive capacities" (1994:373 and see historical references cited therein). Thus, they attribute high hypoplasia frequencies during the middle years of enamel development to multiple environmental stresses, differences in hypoplastic susceptibility in enamel and random factors. This study clearly shows that the age-of-occurrence of hypoplasias is not tied to age-at-weaning (i.e., cessation of breast-feeding) at least in this setting.

Wood (1996) has observed enamel hypoplasias in a skeletal sample of 44 individuals born and raised in early 18th-century frontier settlements of the northeastern United States. She observed peak frequencies in age categories ranging from 2.5–3.0 and 4.0–4.5 years. She argues that these ages are too late to result from weaning, which she describes as having occurred between 1 and 2 years for most populations in colonial North America.

It must be noted that the claims for a positive relationship between enamel hypoplasias and weaning age are based on observations of what can be termed coincidental associations between the calculated ages of occurrence of the two phenomena. The studies by Blakey and colleagues (1994) and Wood (1996) did not find this coincidental association and thus do not support the assumption of a relationship. Some researchers (Jacobi et al., 1992) have also argued that samples which show highest LEH frequencies occurring from 6 to 18 months later than reported weaning ages represent the delayed effects of stress. But it could also be argued that such results do not support a relationship. (Table 1 presents a summary of data from the studies described above.)

Certainly, there are difficulties with reporting "normal" weaning age in any earlier population since the process has been shown to be so variable in studies of contemporary populations. In the case of enslaved African-American populations for which so much documentation on daily life and diet exists, this criticism seems unwarranted. Nevertheless, attempting to test the assumption of a relationship between the two phenomena in an a posteriori fashion will never settle the question except to accumulate negative evidence (Blakey et al., 1994; Wood, 1996). Since it is widely recognized by all researchers that enamel hypoplasias can be

TABLE 1. *Summary information on the studies of enamel hypoplasia discussed in the text*

Study sample	Reference	Peak age of enamel hypoplasia (years)
Chicago (modern)	Sarnat and Schour, 1941	1st year
Dickson mounds (pre-Miss.)	Goodman et al., 1984	3.0–3.5
Dickson mounds (Mid. Miss.)	Goodman et al., 1984	2.5–3.0
Barbados (slave burials)	Corruccini et al., 1985	3.25
Mexico (modern)	Goodman et al., 1987	1.0–3.0
Jordan (modern)	Alcorn and Goodman, 1985	1.0–3.0
Monroe County poorhouse	Lanphear, 1990	2.5–3.0; 3.5–4.0
Florence (19th c.)	Moggi-Cecchi et al., 1994	2.0–3.0
Eastern U.S. (18th–19th-c. slaves)	Blakey et al., 1994	1.5–4.5
South Carolina (19th-c. slaves)	Rathbun, 1987	2.0–4.0
Northeast U.S. (18th-c. colonial)	Wood, 1996	2.5–3.0; 4.0–4.5

produced by a great diversity of stressors, it seems unwise to focus on weaning as a major cause. While there is definite evidence from prospective studies of a relationship between enamel hypoplasia and nutritional stresses (May et al., 1993),[2] the complexity of weaning as a process precludes widespread acceptance of a consistent association between weaning and stress.

Methodological problems

There are clearly various issues to be dealt with when attempting to calculate the individual age at defect formation (for a detailed discussion see Goodman and Rose, 1990). Most researchers follow the same procedure, that is, conversion of measures of the distance of each linear defect from the cementoenamel junction using the chart developed by Goodman et al. (1980) following Swärdstedt (1966) and based on the standard reported by Massler et al. (1941). Confidence intervals for estimated ages of occurrence can be wide (Berti and Mahaney, 1992). It is not always clear that observers have eliminated or dealt with the problem of tooth wear which is common in archaeological samples. Hodges and Wilkinson (1990) discuss the effects of tooth size on determining the age at which hypoplastic lines are formed and provide a sample-specific method which adjusts for varying crown heights between populations, to be used in individuals with little or no occlusal wear. A tooth-specific method which accounts for individual differences in crown height can also be applied (Goodman et al., 1987) but, as Berti and Mahaney (1992) demonstrate, none of these methods can account for all of the sources of age-related variation in tooth enamel height.

There is strong evidence for intratooth variation in hypoplasia distributions. That is, the middle part of the crown in the permanent dentition is more likely to show hypoplasias where the enamel is sensitive to growth arrest (Goodman and Armelagos, 1985a, 1985b). Yet, this observation has not been resolved against efforts to estimate peak ages of occurrence of defects within individuals. This structural bias in enamel formation has also been elaborated by Skinner and Goodman (1992), who demonstrate that reports of peak ages of hypoplasia occurrence can be the result of statistical artifact. In teeth that are maturing at various ages there will be a "heaping up" of observations of stress at the time of peak enamel formation. They cite an illustration from the work of Corruccini and colleagues (1985) that should get around this problem by reporting earliest hypoplasia in each individual. In this case, these authors observed a "markedly platykurtic distribution with mode almost evenly spread over the 1.75–3.5 year range." These results could be consistent with great individual variation over this time period in the age of weaning but they could also equally be consistent with a fairly uniform level of stress unassociated with weaning. It is also suggested that patterns of intra- and intertooth variation in hypoplasia

[2]But the evidence of a relationship between enamel defects and socioeconomic status (as a reflection of health status) is still equivocal (Dobney and Goodman, 1991).

formation are directly related to morphological patterns of enamel formation (Hillson, 1992).

Summary of enamel hypoplasia studies

There are three debatable/questionable assumptions that have been raised by this investigation of the literature. The first is that there is a direct relationship between the peak age of occurrence of defects in dental samples and weaning. Some researchers (Lanphear, 1990; Powell, 1988; Stodder, 1990) have assumed this is true based on earlier statements and yet it has never been directly demonstrated in a prospective study. Others (Corruccini et al., 1985; Moggi-Cecchi et al., 1994) try to make the association with historical data on infant feeding and weaning practices. While there is some useful and reliable historical data on infant feeding practices (see Blakey et al., 1994; Hervada and Newman, 1992; Fildes, 1986, 1992) it is the negative evidence that carries more weight in this type of research approach (Blakey et al., 1994; Wood, 1996).

The second assumption is that estimated age of occurrence of defects is accurate. However, this can be questioned on methodological grounds. Factors which need to be dealt with include: a) the problem of tooth wear; b) developmental, structural and statistical problems that might affect macroscopic observations of hypoplasias and the calculation of their peak age of occurrence.

The third assumption is that weaning and postweaning periods are a time of increased physiological stress for the infant or child. This assumption is rendered complex for a variety of reasons, not the least of which is confusion over the usage of the term weaning as discussed in the introduction. As explained earlier, a "weanling's dilemma" is recognized by infant feeding researchers as a consequence of contaminated complementary foods with diarrheal pathogens or growth faltering when exclusive breast-feeding continues too long. The possibility must be entertained that a "weanling's dilemma" would not be expected in past societies that enjoyed adequate nutrition, reasonably clean water and food and long periods of nursing coupled with the introduction of healthy complementary foods. In fact, by surveying the ethnographic literature, a recent paper has offered just such a claim (Judkins and Baker, 1996). On the other hand, since the health and nutritional status of the mother is an important factor in the quantity and quality of breast milk, problems might continue beyond 1 year. As Fildes (1992) has pointed out, poor, undernourished women may breast-feed their children for several years, in some cases, to avoid frequent pregnancies and because of the difficulty of obtaining artificial foods. Under these circumstances it is not unreasonable to expect growth and health problems in breast-fed infants and children for longer than the post-neonatal period and such a situation might have arisen in some past populations.

Clearly there are limitations to the use of linear enamel hypoplasia data for inferring weaning age in past populations. Enamel hypoplasia has a number of causes so it is perhaps best used as a non-specific stress indicator along with other markers left on bones and teeth.

One other area that has attracted some attention with regard to weaning is that of tooth wear. It might be hypothesized that the earliest appearance of wear in deciduous teeth would indicate that weaning had begun or was completed and consequently associated with the ages of the infants or children in skeletal samples. Molleson (1995) has demonstrated that rates of wear on children's teeth changed throughout the Neolithic period at a single site in northern Syria. She suggests that this indicates that with the advent of pottery and people's ability to prepare soft porridge-like foods from cereal grains that weaning would have occurred earlier and thus affected fertility levels. In most societies, mothers introduce solid foods early while continuing to breastfeed, and because the premastication of foods has been such a widespread practice among many cultures, it may be difficult to use deciduous tooth wear as an indicator of weaning. Buikstra and colleagues (1986) also suggest that weaning and fertility were affected by changes in subsistence and ceramic technologies, based on their paleodemographic research in the American Midwest. They associate an observed increase in fertility, from the Middle Woodland to the Mississippian

period, with a shift to consumption of starchy seeds and the manufacturing of thin-walled ceramic vessels which made it possible to boil seeds in order to soften them, and provide a soft pap for weaning.

CHEMICAL METHODS FOR ESTIMATING WEANING IN SKELETAL SAMPLES

Recently, another approach to estimating the duration of nursing from skeletal remains has been developed, based on the chemical composition of bone. There have been numerous studies of the chemical composition of human bone for the purpose of reconstructing prehistoric diet (reviewed by Schwarcz and Schoeninger, 1991; Katzenberg, 1992; Sandford, 1992, 1993; Ambrose, 1993; Pate, 1994). Some of the same principles used to determine diet from trace element and stable isotope analyses of bone have been utilized to look specifically at infant diet (reviewed by Stuart-Macadam, 1995). In 1984, Sillen and Smith published the first attempt to determine weaning age directly from bone chemistry using the ratio of the trace element strontium to calcium in the bones of infants and young children. They studied skeletal remains from a Middle Eastern sample (AD 800–1300). The basis of using Sr/Ca to estimate the age at which children were weaned is as follows. Strontium is discriminated against in favor of calcium in the mammary gland during the production of milk and, therefore, the Sr/Ca ratio of milk is very low. Strontium is also discriminated against at the placenta, so newborn and nursing infants would be expected to have very low Sr/Ca ratios in their bone mineral. In contrast, the Sr/Ca ratio of plants is high and weaning diets are usually based on cereals. As a result, newborn and nursing infants will have low Sr/Ca ratios in their bone mineral and the ratio will increase as solid foods are introduced into the diet as infants are weaned. In their study, Sillen and Smith observed a gradual increase in Sr/Ca with a peak between 1.5 and 3.5 years of age. Using this method, the interpretation is that the chemistry of the bone changes due to the introduction of foods other than breast milk into the diet.

Hühne-Osterloh and Grupe (1989) carried out a study of northern German skeletons from coffin burials of the 11th and 12th centuries AD in order to compare weaning age, morbidity and mortality. They used Sr/Ca ratios to estimate weaning age and skeletal indicators of stress, including Harris lines and porotic hyperostosis, to estimate morbidity. Results of the trace element analyses indicate that Sr/Ca ratios are highest in the age group 6 months to 2 years then decline in subsequent age groups. Frequencies of pathological lesions suggest that weaning and morbidity are positively correlated in this sample.

In the studies by Sillen and Smith (1984) and Hühne-Osterloh and Grupe (1989), there are observable changes in the Sr/Ca ratios with age (Table 2). Data in Table 2 are taken from Figure 3 of the paper by Sillen and Smith since they do not provide a table of data with mean, sample size and standard deviation. Data in Table 2 from the German site are from the paper by Hühne-Osterloh and Grupe and are supplemented by the more comprehensive data presented in Grupe (1986). In both the Dor and Schleswig studies, sample sizes for infants and young children are quite small and this is a problem common to most studies of archaeological samples. Both Sillen and Smith and Hühne-Osterloh and Grupe apply the use of the "observed ratio" (OR) measure of discrimination of Sr in favor of Ca as first presented by Comar and colleagues (1957). The OR refers to the difference in the Sr/Ca ratio of one phase relative to another phase in the movement of strontium and calcium through the environment and is expressed as:

$$OR_{\text{sample-precursor}} = \frac{Sr/Ca_{\text{sample}}}{Sr/Ca_{\text{precursor}}}$$

where, for example, the sample may be bone and the precursor may be the organism's diet. The measure was originally developed to trace the movement of calcium and strontium through soil to plants to animals to human tissues. Since the ability to discriminate against Sr in favor of Ca improves with the development of the digestive system, the OR from bone to diet for infants is very high (1.0), then decreases with age (0.6 at 1 year; 0.25 at 5 years; 0.18 at 10 years of age) as the

TABLE 2. Sr/Ca ratios from two studies discussed in the text

Dor sample, Israel[1]				Schleswig sample, Germany[2]			
Age (years)	n	Sr/Ca	Range	Age (years)	n	Sr/Ca	SD (total sample)
Birth	2	1.50	1.4–1.6	Birth–0.5	6	0.58	
0.5	3	1.75	1.5–2.0	2	5	0.72	
1	10	2.25	1.5–3.0	4	3	0.63	
2	2	2.50	1.7–2.9	14	6	0.51	
3	5	2.25	1.8–2.8	adult	78	0.53	
8	11	1.60	1.3–2.3				0.16
Adult		1.80					

[1]Estimated from Figure 3 in Sillen and Smith, 1984.
[2]From Table 2 in Hühne-Osterloh and Grupe, 1989, and Table 5 in Grupe, 1986.

ability of the kidney and gut to preferentially excrete Sr relative to Ca improves. The fact that both of these weaning studies found variation in Sr/Ca before applying the OR values for individuals of different ages lends support to the biological significance of their data. Sillen (1986) has pointed out that with diagenesis (chemical exchange in the burial environment) trace element levels in bone tend to become homogeneous within assemblages. If one applies the OR values presented by Rivera and Harley (1965) as reproduced by Sillen and Smith (1984) to a diagenetically altered assemblage, that is one in which Sr/Ca ratios are similar across the age range, they will appear to illustrate nursing and weaning simply due to the change in OR values. The problem of diagenesis must be considered in any attempt to apply the Sr/Ca technique to the question of weaning in archaeological skeletal samples.

Stable nitrogen isotope analysis has also been used to estimate the age at weaning, but in contrast to Sr/Ca ratios, which change with the introduction of other foods, $\delta^{15}N$[3] values change due to the loss of breast milk in the diet. Therefore, the methods are really measuring different events since solid foods may be introduced while children are still nursing. Fogel and colleagues (1989) were the first to investigate the use of stable isotopes of nitrogen for determining weaning age. Their study was based on the fact that nitrogen isotope ratios reflect trophic level differences such that the higher an organism is in a food web, the more positive its $\delta^{15}N$ value will be. Nitrogen isotope values increase by 2–3‰ in each trophic level (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984). Since nursing babies are consuming their mother's tissue, they should have more positive (more enriched in the heavier isotope, ^{15}N) $\delta^{15}N$ than their mothers. Fogel and colleagues collected fingernail clippings (a source of the protein keratin) from mothers and their nursing infants and included longitudinal as well as cross-sectional data. They found that fingernails formed after birth (those clipped at around 3 months of age) showed enriched $\delta^{15}N$ in comparison to the mothers of the infants. This enrichment, which averaged 2.4‰, was seen throughout the time that infants were exclusively breast-fed. Infants that were completely weaned showed $\delta^{15}N$ values similar to those of their mothers approximately 3 to 5 months after weaning. Having established that $\delta^{15}N$ values clearly reflect a trophic level shift in nursing infants, Fogel and colleagues then analysed bone collagen from prehorticultural and horticultural populations from the prehistoric northeastern United States. They tested the hypothesis discussed in a paper by Buikstra and colleagues (1986) proposing that as populations become increasingly dependent on cultivated plants, the length of time that women nurse their children will be shorter and, therefore, interbirth intervals will be shorter. The outcome is argued to be an increase in population size. This assumes that there was a concomitant increase in completed family size and no change in starting and stopping ages among fertile women. Fo-

[3] $\delta^{15}N‰ = \left[\frac{^{15}N/^{14}N_{\text{sample}}}{^{15}N/^{14}N_{\text{standard}}}\right] - 1 \times 1000$

The standard for nitrogen is atmospheric nitrogen (AIR).

gel and colleagues found that the difference between infant and adult $\delta^{15}N$ values was greater in the prehorticultural sites as compared to a site where maize was cultivated. In both groups, $\delta^{15}N$ declined sharply at around 18 to 20 months of age, indicating that breast milk was no longer the main source of protein. Fogel and colleagues clearly show the potential for the use of stable nitrogen isotopes in estimating the age at which breast-feeding declines significantly.

Katzenberg and colleagues (1993) analysed all individuals from a small (n = 29) protohistoric skeletal sample from southern Ontario for stable isotopes of carbon and nitrogen. They found that isotope ratios for both carbon and nitrogen from collagen vary with age. $\delta^{13}C$[4] values are slightly higher in infants, probably reflecting the small trophic level effect in carbon isotopes, estimated to be around +1‰. Higher $\delta^{13}C$ in infants may also be due to the use of maize gruel as a weaning food, and as a food for infants whose mothers died in childbirth or were otherwise unable to nurse their babies (Thwaites, 1896–1901). $\delta^{15}N$ values show a greater trophic level effect with mean differences between infants and others of 1.7‰.

In skeletal samples, the infants and young children available for isotope studies are those individuals who died. It is possible that some deaths resulted from inadequate nutrition, as when mothers die in childbirth, or when there are complications with the digestive systems of infants. Also, some individuals died around the time of birth and would have nursed very little or not at all. Therefore, it is not surprising that some infants in skeletal samples will not show a nursing signal in their collagen $\delta^{15}N$ values and the observed mean differences would be higher if only infants who nursed were included in the comparison.

As part of a comprehensive osteological analysis of European immigrants buried in a small historic cemetery in Ontario (Saunders and Lazenby, 1991), Katzenberg (1991) analysed bone collagen for stable isotopes of carbon and nitrogen. The sample included two newborn infants and three infants aged from 1 to 3 years. The $\delta^{15}N$ of the two newborns were similar to those of the adults in the population while those of the 1-year-olds were the highest in the sample. Because this is a historic family cemetery, sex, age and familial relationships of the people are known. The cemetery contained one mother and infant pair who died in the same month. The $\delta^{15}N$ value of the mother is 11.9‰ as compared to the mean adult value of 12.2‰. The 22-month-old child has $\delta^{15}N$ of 14.2‰. The difference between $\delta^{15}N$ for mother and infant from preserved bone collagen is 2.3‰. While this is only one mother-infant pair, it is a compelling finding since the relationship and cause of death are known and it is unusual to have access to such bone samples. Similarly, the lack of elevated $\delta^{15}N$ in the two newborns is important since their ages are known.

Tuross and Fogel (1994) analysed bone collagen for stable isotopes of carbon and nitrogen from the Sully site skeletal remains, in South Dakota. This large site dates to the 17th and 18th centuries. Of the 36 individuals analysed, 28 were under the age of 5 years. Results of nitrogen isotope analysis showed that the bones of infants between 3 months and 2 years of age averaged 1.6‰ higher in $\delta^{15}N$ than the adults in the population. Infants under 3 months of age have $\delta^{15}N$ values similar to those of adults in the sample since the ingestion of breast milk is not yet recorded in the collagen. $\delta^{15}N$ values decrease in individuals aged 2 years and older and are lower than adult values between 2 and 5 years of age. Based on patterns of $\delta^{15}N$ and $\delta^{13}C$, the authors conclude that infants were probably almost exclusively breast-fed for approximately 1 year. This is based on the high $\delta^{15}N$ values which indicate that sources of nitrogen (i.e., protein) other than breast milk were not significant in the diet. Because collagen reflects the protein source in the diet to a greater degree than it reflects foods low or absent in protein, breast milk will contribute to the carbon and nitrogen incorporated into the collagen molecule to a greater degree than supplementary foods that contain little or no protein (Ambrose and Norr, 1993). The decrease in $\delta^{15}N$

[4] $\delta^{13}C‰ = \left[\dfrac{^{13}C/^{12}C_{\text{sample}}}{^{13}C/^{12}C_{\text{standard}}}\right] - 1 \times 1000$

The standard for carbon is Peedee belemnite (PDB).

after 2 years of age suggests that other foods were probably introduced in significant quantities at that time. $\delta^{13}C$ values are highest among infants, probably due to the smaller trophic level effect of around 1‰ for stable isotopes of carbon.

White and Schwarcz (1994) studied stable isotopes of carbon and nitrogen in bone, muscle, skin and hair of mummies from Sudanese Nubia. They found a maximum enrichment of 3‰ in both bone collagen and muscle tissue from younger infants relative to the adults in the sample. This corresponds to one trophic level and these authors note that the decrease in $\delta^{15}N$ values is a gradual one, suggesting that weaning was gradual. Interestingly, their Figure 4 (White and Schwarcz, 1994) shows a similar pattern to that illustrated by Tuross and Fogel (1994) in that $\delta^{15}N$ values drop below adult values in childhood. White and Schwarcz found this decline in their age category 7–12 years while Tuross and Fogel found it in their >2<6-year-age category.

In an attempt to refine the association between weaning and nitrogen isotope values in bone collagen, Katzenberg and Pfeiffer (1995) analysed a large skeletal sample from a historic Methodist cemetery in Newmarket, Ontario. Sixty-four individuals were analysed for stable isotopes of carbon and nitrogen; of these 23 were under the age of 2 years. A plot of $\delta^{15}N$ values and age at death indicates that elevated $\delta^{15}N$ values peak just before 1 year of age, then drop toward adult values at around 1 year of age. The difference of mean $\delta^{15}N$ for individuals aged 1.5 years and younger (13.8‰) with those over 1.5 years of ge (12.1‰) is 1.7‰. One would expect infants who are exclusively breast-feeding to exhibit $\delta^{15}N$ values of around 3‰ higher than those of adults in the sample, and indeed some individual infants do exhibit such a large increase. However, there are some infants in the sample who show no evidence of having nursed. As Fogel and colleagues (1989) demonstrated in their study of fingernails, there is a lag of 3 months before elevated $\delta^{15}N$ values were registered in the nails that could be clipped. In bone collagen, there will be a mix of collagen laid down in utero and that deposited once nursing has begun. Very young infants will have lower $\delta^{15}N$ values than those infants who are several months of age and have been nursing exclusively. In the Prospect Hill sample, the largest range of $\delta^{15}N$ values occurs around age 6 to 8 months. This suggests that supplementation of other foods began just before that time for some infants, but that there was variation in the age at which new foods were introduced among the people in this sample (Fig. 1).

In a study that directly addresses the relationship between weaning and infant mortality, Schurr (1996) compared $\delta^{15}N$ values from bone collagen with age-specific mortality in a skeletal sample from the Angel site, a Middle Mississippian site in the Ohio Valley of Indiana. In order to sample recently deposited collagen, bone from the metaphyses of the femora was analysed. Schurr found that $\delta^{15}N$ values were highest between 1 and 2 years of age in this sample, suggesting that breast milk supplied most of the dietary protein until 2 years of age, when other protein-rich foods were introduced. Schurr found that infant mortality was highest in the first 6 months. These results indicate that weaning and the associated change in nutrition was not the cause of infant mortality at the Angel site. Schurr suggests that exposure, even in small quantities, to other foods or exposure to substances in the environment may have been the cause of increased mortality in the first year of life. This is consistent with demographic information presented earlier in this paper regarding environmental factors that can affect morbidity and mortality in spite of the protection offered by immunologic components of breast milk.

Finally, Herring and colleagues (1994, submitted) attempt to refine our understanding of the weaning process by combining historic information including parish records, skeletal age at death data and stable isotope analysis from a historic cemetery sample from southern Ontario. Mortality data from the parish records of St. Thomas' Anglican Church in Belleville, Ontario, were compared to the mortality profile derived from the skeletal sample. The biometric method (Bourgeois-Pichat, 1946, 1951a, 1951b, 1952; Knodel and Kintner, 1977) was applied in order to determine if the infants

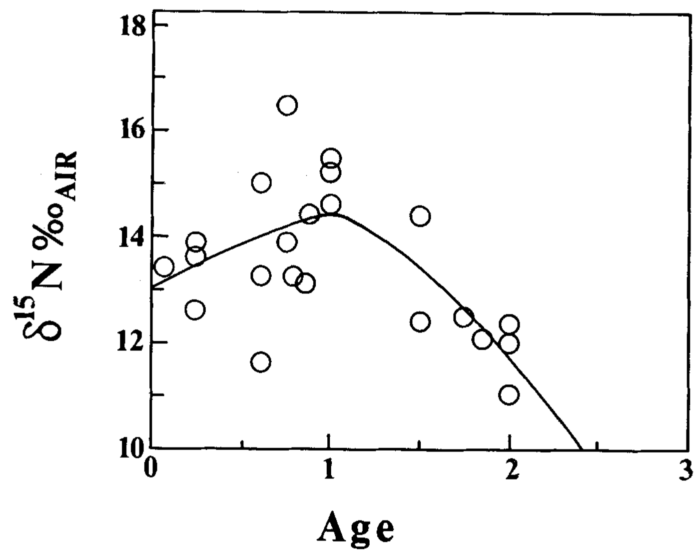

Fig. 1. $\delta^{15}N$ from the Prospect Hill Cemetery, Newmarket, Ontario, for individuals ages birth to 3 years. The individual data points illustrate the range of variation in infant $\delta^{15}N$ values and the curve reflects the drop in $\delta^{15}N$ around 1 year of age. Reproduced from Katzenberg and Pfeiffer, 1995.

were breast-fed and when other foods were introduced into the diet. This information was compared to nitrogen isotope ratios on the same skeletal sample. Herring and colleagues (submitted) conclude that the introduction of alternative foods to breast milk within a sufficiently unsanitary environment resulted in a detectable rise in cumulative infant mortality by 5 months of age even though breast milk remained the main source of protein in the infant diet until about 14 months of age.

Table 3 and Figure 2 illustrate the patterns of $\delta^{15}N$ values in three of the samples discussed above. The MacPherson proto-historic site (Katzenberg et al., 1993) is a small sample of only 29 individuals. The larger samples from two historic cemeteries, Prospect Hill from Newmarket, Ontario (Katzenberg and Pfeiffer, 1995) and St. Thomas' Church from Belleville, Ontario (Herring et al., submitted), illustrate the early increase, then gradual decrease in $\delta^{15}N$ values with age.

Studies by Schurr (submitted) and Herring and colleagues (submitted) indicate that it is the introduction of other foods into the diet in a sufficiently poor environment, and not the cessation of nursing per se that is associated with increased infant mortality. This is in agreement with demographic information such as that of Knodel and Kintner (1977) and suggests that the immunological benefits of nursing do not necessarily protect the infant from environmental pathogens once infants are no longer nursing exclusively. In addition, the immune status of the infant may vary due to variation in the health status of the mother. In the prenatal period, transfer of IgG is related to IgG levels in the mother. After birth, the passive immunity obtained in utero declines but is supplemented by the various antimicrobial factors in breast milk which include: "cellular components such as T and B lymphocytes, macrophages, and neutrophils; immunoglobins IgA, IgD, IgE, IgG and IgM; and other elements such as complement, interferon, iron-binding proteins, lysozyme, bifidus factor and antistaphylococcal factor" (Popkin et al., 1986, page 41). (See also, Lawrence, 1994; Mestecky et al., 1991; Wilkinson, 1981.) The availability of these factors to the infant is related to the immune status of the mother. With respect to development of the infant immune response, there appears to be a period between 4 to 6 months when immunoglobin levels are low (Popkin et al., 1986).

TABLE 3. $\delta^{15}N$ data from three Ontario skeletal samples

	Belleville			MacPherson			Prospect Hill		
Age	n	δ15N	SD	n	δ15N	SD	n	δ15N	SD
Birth–0.5	12	11.8	1.53	5	13.1	0.94	5	13.3	0.49
1.0	7	12.7	0.48	2	14.2	1.20	8	14.2	1.57
1.5	13	13.1	1.42	1	13.8		3	13.6	1.01
2.0	5	11.5	0.91	2	13.8	0.21	5	13.1	1.01
2.5	7	10.6	0.83				2	11.5	0.74
3.0	2	9.6	0.49						
3.5	5	10.5	0.85	2	12.7	1.34			
4.0	5	9.8	0.76				1	11.5	
4.5	4	10.5	0.51				1	13.0	
5.0	3	10.3	0.32				1	12.4	

MacPherson is a proto-historic Ontario Iroquois site (Katzenberg et al., 1993), Prospect Hill (Katzenberg and Pfeiffer, 1995) is a 19th-century Methodist cemetery from Newmarket, Ontario, and Belleville represents the sample from the 19th-century St. Thomas' Anglican Church cemetery from Belleville, Ontario.

These same authors cite several studies from which it is concluded that birth weight, gestational age and maternal nutritional status are all factors which may result in variation in the immune status of the infant.

Summary of bone chemistry studies of weaning

Two different approaches to reconstructing breast-feeding and weaning patterns have been described. The use of Sr/Ca ratios in bone mineral attempts to get at the age at which foods other than breast milk are introduced. Sr/Ca ratios will increase in bone mineral due to the metabolism of other foods. The use of nitrogen stable isotope ratios attempts to get at the age at which breast milk is no longer ingested. Because weaning is a gradual process, the peak difference between infant and adult $\delta^{15}N$ will be from several months after birth (when collagen formed after birth is deposited) to just after the introduction of other foods, when the $\delta^{15}N$ will decrease and approach adult values. Schurr (1996) has developed a model which takes into account collagen synthesis and infant feeding behaviour.

Ideally one could use both methods to identify the weaning process since one marks the beginning of supplementation while the other marks the decline and finally the cessation of breast-feeding. However, diagenesis is a serious problem in dealing with bone mineral analyses. Infant bone is especially porous and there is a greater probability of mineral exchange in the burial environment which may result in homogenizing bones in a cemetery. Sillen's method of extracting mineral of varying solubility (1986) is designed to minimize the problems of diagenesis in studies of strontium in bone. Collagen is less affected by postmortem processes. The collagen may become degraded with differential loss of amino acids; however the integrity of collagen can be checked by various methods, including amino acid analysis and determination of C/N ratios. Both techniques could benefit from a more precise knowledge of the rate at which bone mineral and bone collagen are deposited and the rate at which they turn over in growing infants and children. Schurr's study (1996) addresses the problem of cumulative deposition of collagen by isolating the growing end of bone for the sampling site. Unlike nitrogen isotope studies, where it is quite feasible to sample protein in hair or fingernails without risk to mothers and infants, Sr/Ca has not been monitored in a controlled situation since it would require drawing blood samples or sampling bone mineral.

It is generally recognized that the transition from exclusive breast-feeding to the cessation of breast-feeding is not an abrupt event and that both the change in diet and its reflection in bone will fall along a curve. Newborn infants who become a part of the skeleton record will not normally show any indication of having nursed while infants from several months of age until the time of introduction of other foods should have nitrogen isotope values ranging from 1 to 3‰ greater than the adult females in the sample, depending on whether they were breast-feeding exclusively when the sam-

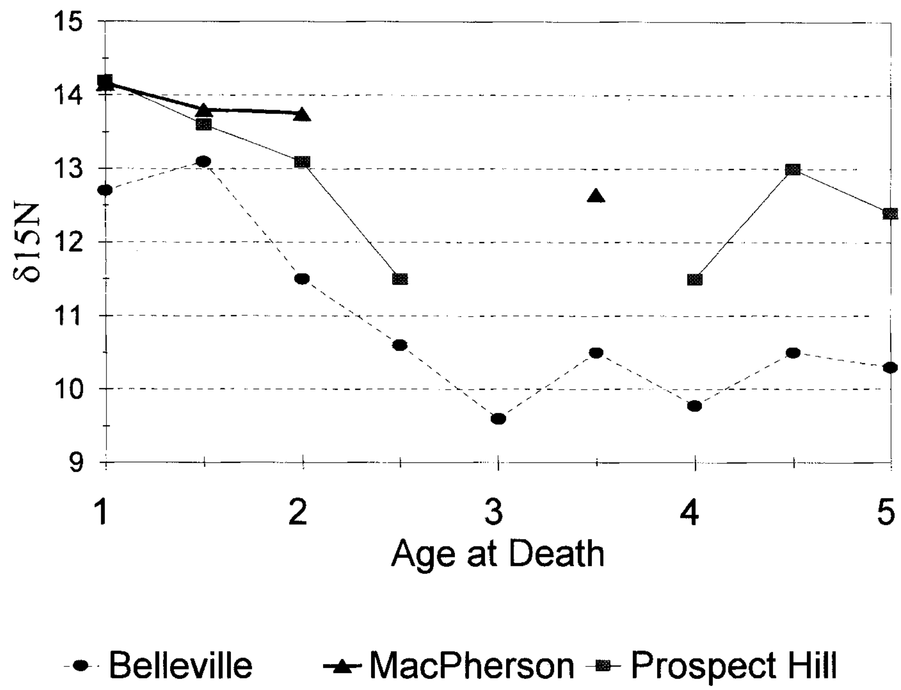

Fig. 2. $\delta^{15}N$ from birth to 5 years of age from three sites (summary data are presented in Table 3). Belleville is the 19th-century St. Thomas' Anglican Church cemetery (Herring et al., submitted); MacPherson is a proto-historic Ontario Iroquois site (Katzenberg et al., 1993) and Prospect Hill is a 19th-century Methodist church cemetery (Katzenberg and Pfeiffer, 1995). The data for MacPherson and Prospect Hill illustrate the problem of small samples where there are sometimes no children in the age range (2–4 years) of interest in attempts to document $\delta^{15}N$ variation due to cessation of breast-feeding.

pled collagen was deposited. It is important to keep in mind that the sample of infants is one of those who did not survive and that their causes of death will vary. Many archaeological skeletal samples have few young children and it is this age segment that will provide the most discerning information on changing patterns of nursing and weaning.

CONCLUSIONS

The literature on breast-feeding, weaning, postpartum ovulation and mortality all points to the broad range of variability among human groups and among individuals within human groups. There are strong cultural influences on infant feeding practices in all societies studied. We have pointed out the complexity of linking causes of morbidity and mortality to weaning owing to such factors as variation in the health of mothers, quality of food and water and other factors in the child's micro- and macroenvironment. It has also been pointed out that local patterns of mortality reflect much larger scale cycles. Demographic transitions, such as the increase in population density with the domestication of plants and animals, are not always uniform among different groups. Finally, breast-feeding is but one of many factors that can affect fertility so it is overly simplistic to try to explain fertility patterns only from information on nursing and weaning. Given these conclusions from the demographic literature, it is no wonder that it is so difficult to get at this information in the skeletal data.

Enamel hypoplasias can be produced by a wide range of stressors and generally occur during the same age span as does the weaning process. Certainly it is likely that some individuals exhibit hypoplasia as a result of sickness associated with the dietary change

and loss of passive immunity that occurs with weaning. However, weaning should not be singled out as a major cause. The introduction of non-milk foods, which usually precedes the cessation of breast-feeding, is an important source of infection, and is at least as important to consider as the later loss of passive immunity with the end of breast-feeding. Studies of living children, such as that of Goodman and colleagues (1987), are needed to establish a link between a particular circumstance and the formation of linear enamel hypoplasia.

The advent of bone chemistry studies may help to improve the case for a link between the formation of linear enamel hypoplasia and weaning when such a link exists. The problem is in comparing the teeth of those who suffered a stressor sufficient to produce hypoplasia with the bones of those who died at about the same age. Ideally, we might hope to analyse bone mineral for Sr/Ca to determine at what age foods other than breast milk were introduced, bone protein for $\delta^{15}N$ to determine when nursing ceased, and skeletal indicators of stress, such as LEH, for which the approximate age of formation can be determined. Problems to be overcome include imprecise knowledge of rates of bone mineral and collagen turnover and the cross-sectional and potentially biased nature, as well as the small size of archaeological samples. Such analyses might better pinpoint the timing of formation of LEH relative to infant diet.

Our views on the potential for getting at such specific information in archaeological samples vary depending on our expertise. An historical demographer might see endless variation and despair at hoping to say very much about weaning and infant mortality in the skeletal record. A skeletal biologist might be a bit more optimistic. We have good evidence that there is a correlation between the duration of nursing and the length of time between births, and that nursing provides passive immunity to infants and young children. It is very likely that physiological changes associated with the introduction of complementary foods, and the developing motor activity of the infant constitute an opportunity for increased morbidity and mortality. It is less clear that the complete cessation of breast-feeding constitutes such an opportunity. We must be aware of the complexity of human groups from the perspective of differences in biology, ecology and culture.

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